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Mazdoor Kisan Shakti Sangathan

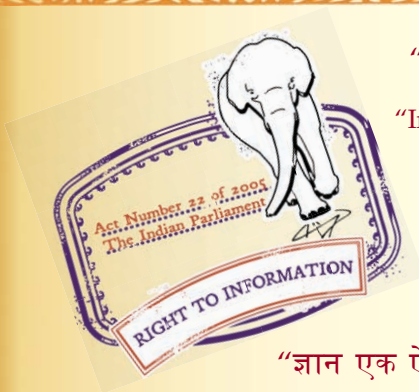
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“पुराने को छोड़ नये के तरफ”

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“Step Out From the Old to the New”

IS 15218-1 (2002): Electrical Insulating Materials -
Determination of the Effects of Ionizing Radiation, Part 1:
Radiation Interaction and Dosimetry [ETD 2: Solid
Electrical Insulating Materials and Insulation Systems]



“ज्ञान से एक नये भारत का निर्माण”

Satyanarayan Gangaram Pitroda

“Invent a New India Using Knowledge”



“ज्ञान एक ऐसा खजाना है जो कभी चुराया नहीं जा सकता है”

Bhartrhari—Nitiśatakam

“Knowledge is such a treasure which cannot be stolen”

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भारतीय मानक

विद्युत रोधी पदार्थ — आयनन विकिरण

के प्रभाव का निर्धारण

भाग 1 विकिरण अन्तर्क्रिया एवं मात्रा मापण

Indian Standard

**ELECTRICAL INSULATING
MATERIALS — DETERMINATION OF
THE EFFECTS OF IONIZING RADIATION**

PART 1 RADIATION INTERACTION AND DOSIMETRY

ICS 29.035.01

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BUREAU OF INDIAN STANDARDS
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NATIONAL FOREWORD

This Indian Standard (Part 1) which is identical with IEC 60544-1(1994) 'Electrical insulating materials — Determination of the effects of ionizing radiation — Part 1 : Radiation interaction and dosimetry' issued by the International Electrotechnical Commission (IEC) was adopted by the Bureau of Indian Standards on the recommendation of the Solid Electrical Insulating Materials Sectional Committee and approval of the Electrotechnical Division Council.

The text of IEC Standard has been approved as suitable for publication as Indian Standard without deviations. Certain conventions are not identical to those used in Indian Standards. Attention is particularly drawn to the following:

- a) Wherever the words 'International Standard' appear referring to this standard, they should be read as 'Indian Standard'; and
- b) Comma (,) has been used as a decimal marker while in Indian Standards, the current practice is to use a point (.) as the decimal marker.

Only the English text in the IEC Publication has been retained while adopting it in this Indian Standard, and as such the page numbers have been given afresh here since they are not the same as in IEC Publication.

It is necessary to define the radiation fields in which materials are exposed and the radiation dose subsequently absorbed by the material.

'Temperature of operation', composition of the 'surrounding atmosphere' and the time interval during which the total dose is received (dose is rate of flux) are important factors which also determine the rate and mechanism of chemical changes.

The establishment of suitable criterion for the evaluation of the radiation resistance of insulating materials depends upon the conditions under which the materials are used. For instance, if an insulation of the cable receives a radiation dose sufficient to reduce to a specified value one or more of the mechanical properties.

This standard (Part 1) is the 'introductory part' in a series dealing with the effect of ionization radiation on insulating materials.

Other parts of the series are:

Part 2 of this standard (to be prepared in due course) will describe procedures for maintaining different types of exposure conditions during irradiation. It also specifies the controls that shall be maintained over these conditions so that desired performances can be obtained. Further, it defines certain important radiation conditions and specifies the test procedures to be used for property change determinations and the corresponding end point criterion.

Part 3 (to be prepared in due course) of this standard will discuss 'various parameters' which can influence radiation induced reactions'.

Part 4 (to be prepared in due course) will provide for classification system for service in radiation environments.

For the purpose of deciding whether a particular requirement of this standard is complied with, the final value, observed or calculated, expressing the result of a test or analysis, shall be rounded off in accordance with IS 2 : 1960 'Rules for rounding off numerical values (*revised*)'. The number of significant places retained in the rounded off value should be the same as that of the specified value in this standard.

Indian Standard

**ELECTRICAL INSULATING
MATERIALS — DETERMINATION OF
THE EFFECTS OF IONIZING RADIATION**

PART 1 RADIATION INTERACTION AND DOSIMETRY

1 Scope and object

This part of IEC 544 deals broadly with the aspects to be considered in evaluating the effects of ionizing radiation on all types of organic insulating materials. It also provides, for X-rays, γ -rays, and electrons, a guide to dosimetry terminology, methods of determining exposure and absorbed dose, and methods of calculating absorbed dose.

2 Normative references

The following normative documents contain provisions which, through reference in this text, constitute provisions of this part of IEC 544. At the time of publication, the editions indicated were valid. All normative documents are subject to revision, and parties to agreements based on this part of IEC 544 are encouraged to investigate the possibility of applying the most recent editions of the normative documents indicated below. Members of IEC and ISO maintain registers of currently valid International Standards.

IEC 544-2: 1991, *Guide for determining the effects of ionizing radiation on insulating materials – Part 2: Procedures for irradiation and test*

IEC 544-4: 1985, *Guide for determining the effects of ionizing radiation on insulating materials – Part 4: Classification system for service in radiation environments*

3 Definitions [15]*

For the purposes of this part of IEC 544, the following definitions apply.

3.1 exposure (X): Exposure is the measure of an electromagnetic radiation field (X- or γ -radiation) to which a material is exposed. The exposure is the quotient obtained by dividing dQ by dm , where dQ is the absolute value of the total charge of the ions of one sign produced in the air when all of the electrons (and positrons) liberated by photons in air of mass dm are completely stopped in air:

$$X = \frac{dQ}{dm}$$

The SI unit of exposure is the coulomb (C) per kilogram: C/kg. The old unit is the roentgen R: $1 \text{ R} = 2,58 \times 10^{-4} \text{ C/kg}$.

* The numbers in square brackets refer to the bibliography given in annex C.

The exposure thus describes the effect of an electromagnetic field on matter in terms of the ionization that the radiation produces in a standard reference material, air.

3.2 electron charge fluence (Q'): The quotient obtained by dividing dQ by dA , where dQ is the electron charge impinging during the time t on the area dA :

$$Q' = \frac{dQ}{dA}$$

3.3 electron current density (j): The quotient obtained by dividing dQ' by dt , where dQ' is the electron charge fluence during the time interval dt :

$$j = \frac{dQ'}{dt} = \frac{d^2Q}{dA dt}$$

3.4 absorbed dose (D): Measure of the energy imparted to the irradiated material, regardless of the nature of the radiation field. The absorbed dose D is the quotient obtained by dividing $d\bar{\epsilon}$ by dm where $d\bar{\epsilon}$ is the mean energy imparted by ionizing radiation to matter of mass dm :

$$D = \frac{d\bar{\epsilon}}{dm}$$

The SI unit is the gray (Gy). The old unit is the rad:

$$1 \text{ Gy} = 1 \text{ J} \cdot \text{kg}^{-1} (= 10^2 \text{ rad})$$

Since this definition does not specify the absorbing material, the gray can be used only with reference to a specific material. The absorbed dose is determined in part by the composition of the irradiated material. When exposed to the same radiation field, therefore, different materials usually receive different absorbed doses.

3.5 absorbed dose rate ($\dot{D}$): The quotient obtained by dividing dD by dt , where dD is the increment of absorbed dose in the time interval dt :

$$\dot{D} = \frac{dD}{dt}$$

The SI unit of absorbed dose rate is the gray per second:

$$1 \text{ Gy} \cdot \text{s}^{-1} = 1 \text{ W} \cdot \text{kg}^{-1} (= 10^2 \text{ rad} \cdot \text{s}^{-1} = 0,36 \text{ Mrad} \cdot \text{h}^{-1})$$

4 Aspects to be considered in evaluating the radiation resistance of insulating materials

4.1 Evaluation of the radiation field

For various types of radiation, the radiation field is described in different ways.

4.1.1 An electromagnetic radiation field may be described in terms of photon flux density and energy distribution. However, for X- and γ -rays up to 3 MeV it is customary to characterize the field in terms of its ionizing effect on air. For this purpose, the quantity "exposure" is used.

4.1.2 A particle field is usually characterized in terms of the current density (fluence rate). When the particles have a distribution of energies, as for electron beams, additional information concerning the energy spectrum is required.

4.1.3 In all cases, the objective is to characterize the radiation field in such a way that the absorbed dose and dose rate in any material placed in the field may be calculated. When different materials are exposed to the same fluence of photons or particles, they may absorb different amounts of energy. The first objective is thus to describe standard methods and procedures for measuring the characteristics of the radiation fields to which insulating materials have to be exposed. Clause 5 meets this objective by presenting a list of radiation dosimetry techniques with the relevant references.

4.2 *Evaluation of absorbed dose and absorbed dose rate*

Techniques have been perfected to obtain – from measurements with radiation detectors such as ionization chambers, calorimeters, and chemical dosimeters – the data for calculating the absorbed dose or absorbed dose rate for a material under irradiation. Clause 5 deals with the reliable and conventional techniques of such measurements. Clause 6 contains the material- and energy-dependent factors to be used in the calculation of absorbed dose or absorbed dose rate in other materials of interest from the measured data for X- and γ -radiation, while clause 7 gives dose estimation methods for electron radiation.

4.3 *Radiation-induced changes and their evaluation*

Although the various types of radiation interact with matter in different ways, the primary process is the production of ions and electrically excited states of molecules which, in turn, may lead to the formation of free radicals. Radiation-generated mobile electrons, which become trapped at sites of low potential energy, are also produced. The first phenomenon leads to permanent chemical, mechanical, and electrical changes of the material; the second results in temporary electrical changes in performance [10].

4.3.1 *Permanent changes*

In polymeric materials, the formation of free radicals during irradiation leads to scission and cross-linking processes that modify the chemical structure of the insulation, generally leading to deterioration of the mechanical properties. This mechanical deterioration frequently gives rise to significant electrical property changes. However, important electrical property changes sometimes occur before mechanical degradation is serious. For example, a change in dissipation factor or in permittivity might become serious for the reliable functioning of a resonant circuit. The extent of scission and cross-linking processes depends on the absorbed dose, the absorbed dose rate, the material geometry, and the environmental conditions present during the irradiation. Because the free radicals sometimes decay slowly, there may also be post-irradiation effects.

4.3.1.1 *Environmental conditions and material geometry*

Environmental conditions and test specimen geometry shall be well controlled and documented during the measurement of radiation effects. Important environmental parameters include temperature, reactive medium, and mechanical and electrical stresses present during the irradiation. If air is present, the irradiation time (flux and dose rate) has also been demonstrated to be a very important experimental parameter because of oxygen diffusion effects and hydroperoxide breakdown rate constants. Both factors are time dependent. The conditions that influence oxygen diffusion and equilibrium concentrations in the polymer shall be controlled. These include: temperature, oxygen pressure, material geometry, and the time during which the dose is applied.

If the effect of simultaneous stresses, e.g. radiation at high temperature, is simulated by sequential stressing, other results are to be expected. Further, there can be differences in results if the sample is first irradiated and then heat aged or vice versa.

4.3.1.2 *Post-irradiation effects*

In organic polymers, there may be post-irradiation effects due to the gradual decay of various reactants, such as residual free radicals. Due allowance should be made for this type of behaviour in any evaluation procedure. The tests should be made at recorded intervals after irradiation, maintaining specimen storage in a standard laboratory atmosphere. The reaction of oxygen with residual free radicals can cause further degradation.

4.3.2 *Temporary effects*

4.3.2.1 Performing measurements during irradiation is not within the scope of this part of IEC 544. Despite this, some basic aspects will be discussed briefly. The temporary effects appear primarily as changes in electrical properties such as induced conductivity, both during and for some time after irradiation. Hence, measurement of the induced conductivity could be used as an evaluation property to determine the temporary radiation effects. These effects are primarily dose-rate dependent.

4.3.2.2 Experience has shown that the induced conductivity is usually not quite proportional to the absorbed dose rate $\dot{D}$, but varies as $\dot{D}^\alpha$, where α is smaller than unity. Hence, the radiation sensitivity is described by the relation:

$$\sigma_i = k\dot{D}^\alpha$$

To determine k and α , at least two measurements are needed. A further complication comes from the fact that k and α also depend on the integrated dose absorbed by the sample.

4.3.2.3 The measurement of the induced conductivity is actually quite delicate, since photoelectrons and Compton electrons in the electrode materials will tend to perturb the intrinsic induced current of the specimen. Ionic currents through the ionized atmosphere will also introduce errors in the measurement if they are not eliminated. Experimental procedures eliminating most of the disturbing effects, while remaining relatively simple, should be defined.

4.3.2.4 It would be convenient to use a simple figure such as the induced conductivity σ_i or σ_i/σ_o , its ratio to the dark conductivity σ_o measured in the same experimental conditions, per unit dose rate to characterize the sensitivity of the materials to temporary effects.

5 Dosimetry methods

5.1 General

Absolute methods are those that will provide a determination of the exposure, current density, or the absorbed dose by means of physical measurements that do not depend on a calibration of the instrument in a known radiation field. This definition does not directly imply the accuracy of an absolute method; but through the results of much research on the instrumental techniques and the fundamentals of the radiation-induced reactions, there are absolute methods, such as calorimetry, that are widely considered as primary dosimetry standards. These procedures are not regularly used in studies of radiation effects but are available in national and international standards laboratories for calibration of radiation sources. For photon sources, the calibration accuracy is within 2 % to 3 %. These methods can be used as reliable standards of comparison between different laboratories.

In addition to the absolute standard methods, there are many other dosimeters that have been calibrated against them and which have become extensively utilized as relative dosimeters for measuring the absorbed dose [21]. These are based on a wide variety of measurable chemical reactions or energy transformations resulting from the energy imparted to the dosimetry material as a result of the interaction with the radiation field. A large number of radiation sensors such as plastic films and inorganic solids have been used as dosimeters; these are relatively easy to handle and provide easy-to-analyse responses. In many cases, there are definite advantages in using them where the required accuracy is less stringent.

5.2 Absolute methods

5.2.1 Gamma-rays

5.2.1.1 Free-air ionization chambers are used to measure exposure X up to 3 MeV. That is, they are designed to measure the quantity of charge dQ produced in air and the mass dm of air where the ionizing electrons are liberated.

5.2.1.2 Cavity ionization chambers are radiation detectors that can be used to measure exposure if $\dot{D}$ is not too high and equilibrium conditions are ensured [9]. If a cavity ionization chamber is used to measure the absorbed dose in a particular medium, both wall and gas should be matched to this medium. Two materials may be said to be matched for a particular type of radiation if the absorption of this radiation leads to the same flux density and energy distribution of secondary ionizing particles in both media.

5.2.1.3 Calorimeters operate by absorbing energy from the radiation field in which they are placed; they retain this energy until it is converted to thermal energy and this heat quantity is evaluated by measuring the rise in temperature of the system [4]. The heat capacity of the system may be calibrated electrically by measuring the amount of electrical power input required to produce the same temperature rise as the radiation. In some systems, the conversion of energy into chemical form by exochemical or endochemical reactions has been noted to produce slight deviations for which corrections can be made. However, since the conversion of absorbed radiation energy to heat establishes a system that measures energy deposition almost independent of radiation quality, the calorimeter constitutes an absolute method against which other standard methods have been calibrated.

5.2.2 *Electron beams*

5.2.2.1 Dosimetric or radiometric methods will provide a determination of absorbed dose or electron fluence by means of physical measurements without any calibration. There are two absolute methods that are considered as dosimetric or radiometric references: the one is calorimetry, and the other electron current densitometry. These absolute methods are used mainly for calibration of routine dosimeters, and it is generally difficult to determine depth-dose distribution without the use of routine film dosimeters.

5.2.2.2 The calorimeters are used to measure absorbed dose or energy fluence. Measurement of the absorbed energy per unit area of the target enables the calibration of absorbed dose and of a routine dosimeter by integrating a relative depth-dose distribution, if the relative depth-dose distribution in the same target material is given by using the routine dosimeters with high spatial resolution. Simple quasi-adiabatic methods can be used as a partial-absorption type [25] and a total-absorption type calorimeter.

5.2.2.3 The electron current density measurement is a radiometric method [33] to measure electron charge or current per unit area of radiation fields of electron accelerators. This method is not a dosimetric method, but enables the calibration of absorbed dose, if the mean electron energy impinging on the charge absorber of the densitometer and the relative depth-dose distribution in the same absorber material are given by using a routine dosimeter. The Faraday cup has been widely used for charge measurement of electron beams, but it is not suitable for giving accurate values of electron charge or current per unit area for broad electron beams with wide angular distribution. A simplified method using an assembly of graphite charge absorbers without a vacuum chamber is useful for scattered broad beams from electron accelerators [33], [35].

The effective absorbing area is accurately defined by special arrangement of the absorber assembly and electron backscattering correction in consideration of oblique incidence. The influence of ionized charge of the surrounding air can be avoided by minimizing extraneous electric field formation around the centre absorber.

5.3 *Relative methods*

5.3.1 Chemical conversion dosimetry is based on the principle that certain reactions take place upon irradiation to an extent directly proportional to the absorbed dose. The ferrous sulfate (Fricke dosimeter) method is a well-defined standard of this type and is the most reliable. It is widely used and suitable for comparisons between different laboratories [4], [9], [1]. Other systems are very important because of their utility in extending the range of the ferrous sulfate method. The amino acid type (alanine) dosimeter is recommended by IAEA as a transfer standard [28], [29], [20]. Plastics, dyed or undyed, are also suitable as chemical dosimeters [18], [22], [23], [34], [32].

5.3.2 Other relative methods based on physical effects are photoluminescence or thermoluminescence [3], [26], [8].

5.3.3 Effective utilization of relative dosimeters is limited to conditions similar to those under which they have been calibrated, if the dosimeters show variations in response to environmental conditions (temperature and humidity before and after irradiation, atmosphere, light, etc.), dose rate, and radiation spectrum. Other imprecisions are due to instability before and after irradiation, batch-to-batch variation, non-linearity in the response characteristics, size variation, impurity or chemical effects, etc.

5.3.4 In some cases calibration constants or calibration curves obtained with γ -rays can be applied for electron beams if the dosimetry characteristics do not depend on the difference of irradiation parameters between γ -rays and electron beams, such as electron energy spectrum, dose rate, irradiation time, temperature during irradiation, etc.

5.4 *Recommended methods for measuring absorbed dose*

5.4.1 Table 1 gives a non-exhaustive list of absolute and secondary methods with some of their characteristics, such as:

- range of absorbed doses and absorbed dose rates;
- influence of the radiation energy;
- influence of temperature or humidity;
- material and thickness of film or target;
- type of read-out;
- observations of practical interest;
- bibliographical references.

5.4.2 A difficulty inherent in the dosimetry at high absorbed doses or high absorbed dose rates, such as is customary with the irradiation of insulating materials, arises from possible radiation effects or damage produced in parts of the dosimeters (e.g. damage to insulators of ionization chambers).

Special tests and procedures may be required to avoid disturbances of this type. More complete reviews of most of the methods listed can be found in [4] and in the references in table 1.

6 Calculation of absorbed dose from X- or gamma-radiation

6.1 General

The absorbed dose is the parameter for use in relating the effects of radiation in insulating materials.

This recommended practice presents a technique for calculating the absorbed dose in a material from the knowledge of the X- or γ -radiation field and the composition of the material [1], [2]. From the absorbed dose in one material, the absorbed dose in any other material exposed to the same radiation field may be calculated.

6.2 Calculation of the absorbed dose from a measurement of exposure [13], [14]

6.2.1 Absorbed dose has become the basis for comparison of effects of different radiations and it has become necessary to determine the absorbed dose deposited in the irradiated material. The exposure measured in free air at the location of the specimen may then be utilized as the basic information from which the absorbed dose is to be calculated. The following subclauses contain the formulae to be used in this calculation. Tables 2 and 3 supply the necessary numerical factors and give examples for calculation.

6.2.2 The absorbed dose D_m in a material m is calculated with the equation:

$$D_m = f_m X \quad (1)$$

where the numerical factor f_m is the quotient of absorbed dose per unit exposure. To calculate f_m , the composition of the material and the numerical factors f_i for the included elements i are needed according to the equation:

$$f_m = \sum_i a_i f_i \quad (2)$$

where

a_i is the mass fraction of element i in the material

f_i is the absorbed dose per unit exposure for element i .

6.2.3 Table 2 gives values of f_i in J/C for photon energies between 0,1 MeV and 3,0 MeV for the elements listed (see annex B for the derivation of f_i values). The values of f_i are valid only under conditions of charged-particle equilibrium (see annex A for explanation).

Table 3 gives the values of f_m calculated with equation (2) for some of the commonly used materials for photon energy levels of 1 MeV and 0,1 MeV.

6.2.4 For various organic compounds irradiated at photon energies in the range between 0,5 MeV and 1,5 MeV, equation (2) for f_m may be approximated as:

$$f_m = (32,9a_H - 1,94a_F - 1,55a_{Cl} - 1,16a_P + 33,7) \text{ J/C}$$

6.3 Calculation of absorbed dose in one material from that in another

6.3.1 The numerical factors are also applicable for the comparison of absorbed dose in different media without reference to the exposure, provided the latter is held constant. From equation (B.2) in annex B, it is seen that, for constant exposure, the ratio between the f_m values for any two media equals the ratio between their mass energy-absorption coefficients $(\mu_{en}/\rho)_m$; hence the ratio equals the ratio between the absorbed doses. The absorbed dose in medium 1, D_1 , can be calculated from the absorbed dose D_2 in medium 2 using the numerical factors f_1 and f_2 by the equation:

$$D_1 = \frac{f_1}{f_2} D_2 \quad (3)$$

6.3.2 When chemical dosimetry is employed, the measured chemical change may be converted directly to the absorbed dose. By utilizing the ratio of f_m values, one can calculate the absorbed dose in any material from a knowledge of the absorbed dose in a chemical dosimeter when the incident photon energy is known (within the limitations stated in 6.4).

6.3.3 For example, if one measures an absorbed dose in the Fricke dosimeter to be $D_{\text{Fricke}} = 5$ Gy for a 1 h exposure in a ^{60}Co irradiator and it is desired to determine the absorbed dose in a specimen of polyethylene in the same irradiator for 1 h, one proceeds as follows.

The Fricke dosimeter has mass fractions of $a_H = 0,11$; $a_O = 0,88$, and $a_S = 0,013$, respectively. Table 2 gives the f_i values for 1,0 MeV photon energy. Substituting the a_i and f_i values in equation (2), one obtains $f_{\text{Fricke}} = 37,4$ J/C. From table 3, $f_{\text{PE}} = 38,2$ J/C and with equation (3) the absorbed dose in polyethylene is equal to:

$$D_{\text{PE}} = \frac{f_{\text{PE}}}{f_{\text{Fricke}}} \times D_{\text{Fricke}} = 1,02 \times 5 \text{ Gy} = 5,1 \text{ Gy}$$

6.3.4 In the same way, the numerical factors in table 3 may be used to convert the absorbed dose in any material listed to the absorbed dose in any other material listed provided the energy of the incident radiation is either 0,1 MeV or between 0,5 MeV and 1,5 MeV.

6.4 Depth-dose distribution (limitations)

6.4.1 Since the absorbed dose distribution through the specimen being irradiated will vary and is a function of the thickness of the specimen, its density, and the energy of the incident radiation, it is necessary to decide how much variation in dose one is willing to tolerate as the radiation penetrates the specimen. The most commonly used irradiation facilities have radiation sources in the energy range of 0,5 MeV to 1,5 MeV. If, for a point source, one arbitrarily sets a limit of 25 % for the difference between the absorbed dose at the front and rear of the specimen (25 % attenuation through the specimen), then the specimen thickness is limited to 2,8 cm for 0,5 MeV and 5,0 cm for 1,5 MeV radiation, assuming no build-up, a specimen of unit density equal to 1 g/cm³ and unidirectional radiation (see annex A). For other source geometries (e.g. slab sources) these thicknesses will be significantly different.

6.4.2 Figure A.3, in annex A, is a plot of thickness as a function of energy of a sample for 10 % and 25 % attenuation through a specimen of unit density equal to 1 g/cm³ for unidirectional radiation. The curves will shift to the left for higher-density material and to the right for lower-density material. The accurate thickness for 10 % or 25 % attenuation in the specimen will be the value obtained from figure A.3 divided by the ratio of the electron density of the specimen to $3,3 \times 10^{23} \text{ g}^{-1}$. Since the curves are calculated on the basis of attenuation only, and build-up in the thicker specimens is neglected, the curves represent a maximum attenuation for a given energy and thickness, and for unidirectional radiation. Non-unidirectional radiation results in larger attenuation.

7 Dose estimation methods for electron radiation

7.1 General

7.1.1 In this clause, dose estimation methods for electron beams are recommended mainly for an electron energy range of several hundred keV to several MeV and for a dose range of kGy to MGy.

7.1.2 The radiation field of an electron beam is usually characterized in terms of electron energy spectrum and electron current density, which is the electron charge impinging on a unit area of the irradiated plane per unit time. In the usual operation of an electron accelerator with a beam scanner, the instantaneous electron current density at the point of interest in the irradiated plane changes periodically depending on the scanning frequency. Practically, the radiation field is characterized in terms of the mean energy of electrons transmitted through the beam window and the air gap, and of the electron current density averaged over a scanning period. The mean electron energy at the surface of the sample, E_m , is evaluated by the following equation:

$$E_m = E_0 - \Delta E_w - \Delta E_a \quad (4)$$

where E_0 is the initial electron energy before incidence on the beam window, and ΔE_w and ΔE_a are the mean energy losses of the transmitted electrons in the beam window and the air gap, respectively. Each energy loss is roughly equal to the product of the collision stopping power and the thickness expressed in g/cm², or roughly evaluated by equation (6) when the thickness is much smaller than the electron range.

7.1.3 The distribution of the mean electron current density in the radiation field determines approximately the lateral distribution of mean absorbed dose rate in the material. The lateral distribution in the direction normal to the scanning axis of the radiation field usually has a Gaussian profile. The full width at half maximum of the Gaussian distribution depends on the electron energy, the atomic number and the thickness of the beam window, and the air-gap distance from the beam window to the specimen to be irradiated. For stationary irradiation, the lateral dose uniformity in the material is determined mainly by the distribution of the mean electron current density. Irradiation using a conveyor system moving with constant velocity provides a uniform lateral dose distribution in the material, if the scanned beam intensity is uniform in the direction of the scanning axis.

7.1.4 For stationary irradiation, the dose rate averaged over the scanning period is usually estimated to be the mean dose rate. Two factors complicate its estimation: i) overlapping of the beam, ii) the movement of the sample on a conveyor system.

7.1.5 Dose uniformity throughout the material is determined by the depth-dose distribution, which is usually independent of the lateral dose distribution in the slab layer of the material. A typical depth-dose distribution in a homogeneous material obtained with electron accelerators is shown in figure 1. The depth-dose distribution is characterized by two depth regions: a dose build-up region and a dose declining region. The useful range R_u roughly increases linearly with electron energy when it is higher than 1 MeV, but the dose variation with depth is much larger in electron-beam irradiations than in γ -ray irradiations. The ratio of the surface dose to the peak dose and the useful range depend on several irradiation parameters such as electron energy, atomic composition of the material, thickness of the beam window, the air-gap distance, etc. In typical irradiating conditions, the ratio is 0,6 – 0,8 for electron energy higher than 1 MeV.

7.1.6 The depth-dose distribution in the material per unit electron fluence can be calculated as a part of energy deposition function, $I(z)$, in a three-layer slab absorber (beam window, air layer, and the specimen) [31], [17], when a slab-layer material is moved through the radiation field in the direction perpendicular to the direction of the beam scanning, assuming that a monoenergetic and plane-parallel electron beam impinges normally on the beam window. An example of calculated results of $I(z')$ (z' = total depth in three layers) for a slab layer of polyethylene exposed to 1 MeV electrons is shown in figure 2. The difference of $I(z')$ between the three layers is not equivalent to the difference of absorbed dose. Figure 3 shows a comparison of relative depth-dose distributions for typical insulating materials which were measured for the same irradiation conditions. The difference between typical organic insulators is not negligible, which is due to the difference of the mass collision stopping power [7] and the mass multiple scattering power [16] that depends mainly on the content of hydrogen and the effective atomic number $\langle Z \rangle$.

7.2 Recommended procedures for electron-beam dosimetry

Table 1 gives a list of absolute and relative methods with some of their main characteristics. A recommended check list for dosimetry procedures includes the following [12]:

- 1) electron energy in relation to thickness of the specimen;
- 2) dose range to be covered in the test;
- 3) mean dose rate in relation to temperature rise in the specimen and irradiation time allowed for the test;
- 4) dose uniformity within the specimen required for the test:
 - a) limit allowed for dose uniformity within the thickness,
 - b) limit allowed for lateral dose uniformity within the specimen;
- 5) irradiation method, taking into consideration the number of specimens, their size, the temperature rise, and the dose uniformity in the specimen (stationary or scanned irradiation);

- 6) accuracy and precision limit required in the dosimetry;
- 7) selection of dosimeters using the following criteria:
 - a) measurable dose range,
 - b) thickness of dosimeter giving a defined spatial resolution of the dose reading,
 - c) precision or reproducibility at specified dose levels,
 - d) variation of response within the expected dose-rate ranges,
 - e) limited variation of response during and after irradiation with environmental conditions (effect of light, temperature, humidity, gases, storage),
 - f) permanence of reading or stability of dose indication,
 - g) availability of well-developed and proven standard measurement procedure,
 - h) simplicity of handling and read-out procedure,
 - i) availability of dose reader for exclusive use of the dosimeter,
 - j) reproducibility between different batches,
 - k) cost;
- 8) other irradiation parameters (beam current, scan width, air-gap distance, conveyor speed, backplate for irradiation, temperature, humidity, instantaneous dose rate, backscattering effect, oblique electron incidence, charge accumulation in the insulator, etc.).

7.3 *Electron-beam irradiation*

7.3.1 One-sided electron-beam irradiation of a specimen of the insulating materials is usually conducted in two sample arrangements, shown in figure 4, taking into consideration the dose variation within the specimen due to the depth-dose distribution: a) specimen and a backplate of the equivalent material; and b) specimen sandwiched between two plates of the equivalent material. The total thickness of the irradiation set-up should be greater than the electron range. Two-sided irradiation is conducted for specimens which are thick compared with the electron range.

7.3.2 Acceleration voltage is basically chosen to satisfy the requirement of dose uniformity within the specimen thickness. Beam current and other irradiating conditions such as air-gap distance, beam-scanning parameters, mechanical scanning parameters of the conveyor system, etc. are usually chosen to minimize temperature rise in the specimen during irradiation and to optimize the radiation utilization efficiency.

7.4 *Methods for measuring depth-dose distributions*

7.4.1 Measurement of depth-dose distributions in the insulating materials of interest is the most typical practice in electron-beam dosimetry. There are two basic methods for depth-dose measurement using film dosimeters in a stack of insulating materials and wedge-shaped insulating materials, each with a few variations as shown in figure 5.

7.4.2 In the uniform stack method (see figure 5a), dosimeter films themselves are stacked as the equivalent insulating materials up to a thickness greater than the electron range. This method gives the depth-dose distribution in the dosimeter material, and can be applied for materials with a composition similar to the film. This may be the only method to measure the depth-dose distribution for low-energy electron beams (< 300 keV).

7.4.3 In the alternate stack method (see figure 5b), dosimeter films and slab layers of an equivalent insulating material that has a composition similar to the film are stacked alternately. This method may be applied for relatively high-energy electron beams.

7.4.4 In the shift insertion method (see figure 5c), small chips of dosimeter films are inserted into the stack of equivalent insulating materials in such a way that the dosimeter films do not overlap.

7.4.5 When the stacked insulating materials are uniformly exposed to electron beams in the lateral direction, the absorbed dose D_i in the insulating materials of interest is given by the formula:

$$D_i = f \cdot D_d = \frac{(S/\rho)_{\text{col},i}}{(S/\rho)_{\text{col},d}} D_d \quad (5)$$

where D_d is the absorbed dose in the dosimeter material, $(S/\rho)_{\text{col},i}$ and $(S/\rho)_{\text{col},d}$ are the electron mass collision stopping power of the insulating materials and the dosimeter material, respectively, averaged over the approximate electron energy spectrum for the two materials [24].

Tables 4 and 5 show the basic properties of some important insulating materials and of other materials, and the mass stopping power for electrons in the materials. The electron energy spectrum for the inserted dosimeter films depends on the depth in the stacked insulating materials and generally it is not easy to evaluate the spectrum at each depth. However, the ratio f is only slightly energy dependent over the energy range of interest in radiation resistance tests of insulating materials as shown in table 5. Rough estimation of the average energy of the electron spectrum in the dosimeter material of interest provides sufficient information to evaluate the ratio f with appropriate accuracy. The mean electron energy, E_n , as a function of depth in typical water-equivalent insulating materials, is roughly estimated by the formula:

$$E_n = E_m (1 - z/R_{\text{ex}}) \quad (6)$$

where E_m is the energy of incident electrons (MeV), z the depth in the insulating materials (g/cm^2), and R_{ex} the extrapolated electron range (g/cm^2) which is defined for electron transmission curves normally incident on the insulating materials [30]. The extrapolated electron ranges are listed for several important materials in table 6 as a function of electron energy. Mass stopping powers for composite materials and compounds can be found in reference [12] and [7].

7.4.6 In the linear-wedge method (see figure 5d), a dosimeter film is sandwiched between two equivalent insulating materials, the upper of which is in the shape of a linear wedge. The depth-dose distribution in the dosimeter material is measured by a densitometric trace on the irradiated dosimeter film. The depth-dose distribution in the insulator is given by dose conversion with equation (5).

7.4.7 In the stepped wedge method (see figure 5e), the upper insulating material of the sandwich is in the shape of a stepped wedge. The linear wedge method has two practical disadvantages especially in relatively low-energy electron-beam dosimetry; one is the difficulty in preparing a small linear wedge with an acute angle, and the other is the uncertainty in determining absolute depth in the insulating materials. The stepped wedge with an acute angle can be prepared using a number of insulating material films of different lengths in layers. Although it results in a discontinuous depth-dose profile just like a step function, the distribution is determined as a function of accurate depth in the insulating materials.

7.4.8 Another problem is charge accumulation in thick wedges induced by electron-beam irradiation, giving rise to strong internal electric field which may suppress the penetration of incident electrons [11]. The charge accumulation is much less in stacked films than in the bulk insulating materials of the same thickness, because of a relatively large amount of electric leakage along the surface of the films.

Table 1 – Current methods recommended for measuring absorbed dose

Method	Type of read-out	Dose range (Gy)	Dose-rate range (Gy/s)	Energy	Temperature	Comments	Reference
<i>Absolute methods</i>							
Calorimeters	Temperature	10^{-1} to 10^4	From 3×10^{-3} to about $1,5 \times 10^4$	Independent of energy	No effect	Adiabatic type most acceptable. High precision with thermistor sensors. Direct electric reading well suited for high-intensity fields	[4] [27]
Cavity-type ionization chamber	Electric current		From very low to 3×10^2	Specified by manufacturer	No effect	Commercially available devices. Direct electric reading. Very sensitive method well suited for low-dose and dose-rate measurements	[9] [33] [35]
<i>Relative methods</i>							
Chemical conversion							
Ferrous sulfate (Fricke dosimeter)	Spectrophotometry	4×10^{-2} to 4×10^2	Up to 30	Independent of energy in the range of 0,66 MeV to 16 MeV	Small effect in the range 0 °C to 50 °C during irradiation, very sensitive for spectrophotometric read-out	Easily prepared in the laboratory	[4] [1] [9]
Ceric sulfate	Spectrophotometry	5×10^2 to 10^7	Up to 10^7	Similar to ferrous sulfide	Small effect	Sensitive to impurities	
<i>Gas evolution</i>							
Polyethylene	Hydrogen gas yield	10^2 to 10^7	From 3×10^{-3} to 3×10^2	Independent	Below 80 °C	Easy read-out	

Table 1 – Current methods recommended for measuring absorbed dose (*continued*)

Method	Type of read-out	Dose range (Gy)	Dose-rate range (Gy/s)	Energy	Temperature	Comments	Reference
<i>Optical density</i>							
Polymethylmethacrylate, dyed and undyed	Spectrophotometry	2×10^3 to 3×10^4	Up to 100		Small effect		[5] [36]
Radiochromic film	Spectrophotometry	10^3 to 10^6	Up to 10^4 at least		No effect up to 50 °C	Sensitive to UV light	[18] [22] [23]
Cellulose triacetate film	Spectrophotometry	10 to 3×10^5	Up to 10^7 at least		No effect		[34] [32]
<i>Photoluminescence</i>							
Silver-activated phosphate glass	Luminescence	10^{-4} to 10^2	Up to 10^7 at least	10 to 30 times greater response for exposure at 30 keV to 1,2 MeV, depending on type and size of glass pieces used. Improved by shielding	Must apply correction factors for exposure deviations from 25 °C	Read-out instruments and selection of glasses available commercially	[3] [9] [6]
<i>Thermoluminescence</i>							
Lithium fluoride	Luminescence	10^{-4} to 3×10^2	Up to 5×10^2 at least	Approximately 1,5 times greater response for exposure at 50 keV than at 1,2 keV	Time-stable glow peak at 210 °C	Read-out instruments and dosimetry-grade material are available commercially. Unsuitable for mixed γ and neutron fields	[19] [9] [26] [8] [6]
<i>Free radicals</i>							
Alanine	ESR spectrometry	5×10^{-1} to 10^6			Small effect	Very good stability and reproducibility	[28] [29] [20]

Table 2 – Numerical factors f_i (absorbed dose per unit exposure) in J/C, for calculating the absorbed dose from exposure for elements included in insulating materials – Calculated with equation (B4) in annex B (For using the old CGS units, rad and roentgen see note in annex B)

Photon energy (MeV)	H	C	N	O	F	Si	S	Cl	P
0,10	59,3	31,1	32,4	33,8	34,7	64,7	87,2	99,2	72,9
0,15	64,7	33,0	33,4	33,8	32,7	41,1	47,3	48,8	42,2
0,20	66,3	33,6	33,6	34,1	32,3	36,7	38,8	38,8	36,7
0,30	66,7	33,7	33,8	33,8	31,9	34,6	35,2	36,8	33,9
0,40	66,7	33,6	33,7	33,7	31,9	34,0	34,3	33,1	32,0
0,50	66,7	33,7	33,7	33,7	31,9	33,6	34,0	32,7	32,7
0,60	66,7	33,7	33,7	33,7	32,0	33,7	33,8	32,5	32,7
0,80	66,7	33,6	33,7	33,7	31,9	33,6	33,4	32,3	32,7
1,0	66,7	33,6	33,7	33,7	31,9	33,4	33,7	32,1	32,4
1,5	66,7	33,7	33,7	33,7	31,8	33,7	33,6	31,9	32,4
2,0	66,7	33,7	33,7	33,7	31,9	33,8	33,8	32,4	32,8
3,0	65,1	33,5	33,7	33,8	32,2	34,5	34,5	33,5	33,5

Example of application

For polytetrafluoroethylene, the numerical factor f_{PTFE} for 1 MeV photon energy shall be calculated. Polytetrafluoroethylene (PTFE) has the approximated formula $(\text{CF}_2)_n$ (disregarding chain ends, unsaturation, and impurities); hence, the mass fractions of C and F are $a_{\text{C}} = 0,24$ and $a_{\text{F}} = 0,76$ respectively.

Table 2 gives $f_{\text{C}} = 33,6$ J/C and $f_{\text{F}} = 31,9$ J/C for 1 MeV photons. Substituting these values in equation (2) gives:

$$f_{\text{PTFE}} = (0,24 \times 33,6) + (0,76 \times 31,9) = 32,3 \text{ J/C}$$

Table 3 – Numerical factors f_m (absorbed dose per unit exposure) in J/C, for calculating the absorbed dose from exposure for some important insulating materials and other compounds
(For using the old CGS units, rad and roentgen see note in annex B)

Material		f_m (J/C)	
		1 Mev	0,1 MeV
Polystyrene	$(CH)_n$	36,4	33,3
Polyethylene	$(CH_2)_n$	38,2	34,9
Polyamide-6	$(C_6H_{11}ON)_n$	36,8	34,5
Polydimethyl siloxane	$(C_2H_6OSi)_n$	36,0	47,0
Ethylene polysulfide	$(C_2H_4S_4)_n$	34,9	77,9
Vinylidene chloride copolymer	$(C_4H_5Cl_3)_n$	33,7	77,5
Polytetrafluoroethylene	$(CF_2)_n$	32,3	33,8
Polychlorotrifluoroethylene	$(C_2F_3Cl)_n$	32,2	53,5
Polyvinyl chloride	$(C_2H_3Cl)_n$	34,5	70,5
Polyvinylidene chloride	$(C_2H_2Cl_2)_n$	33,3	81,4
Polyvinyl pyrrolidone	$(C_6H_9NO)_n$	36,4	33,7
Polyvinyl carbazole	$(C_{14}H_{11}N)_n$	35,7	32,9
Polyvinyl acetate	$(C_4H_6O_2)_n$	36,0	34,1
Polymethyl methacrylate	$(C_5H_8O_2)_n$	36,4	34,1
Tributyl phosphate	$(C_4H_9)_3PO_4$	36,8	39,5
Fricke dosimeter	–	37,4	37,2
NOTE – The data for 1 MeV are valid in the range from 0,5 MeV to 1,5 MeV approximately. These data may also be used for ^{60}Co and ^{137}Cs γ -rays and for 2 MeV to 3 MeV X-rays.			

Table 4 – Basic properties of some important insulating materials and other materials

<i>Material</i>	<i>Chemical formula</i>	$\langle Z \rangle = {}^1$	$\langle A \rangle = {}^2$	<i>Density</i> (g/cm ³)
Carbon (graphite)	C	6	12,011	2,25
Water	H ₂ O	7,22	13,00	1,00
Air (dry)		7,38	14,77	1,205 × 10 ⁻³
Polyamide (Nylon-6)	(C ₆ H ₁₁ ON) _n	5,92	10,80	1,14
Polyethylene	(CH ₂) _n	5,28	9,26	0,94
Polyethyleneterephthalate	(C ₁₀ H ₈ O ₄) _n	6,46	12,41	1,40
Polymethylmethacrylate	(C ₅ H ₈ O ₂) _n	6,24	11,56	1,19
Polystyrene	(CH) _n	5,61	10,44	1,06
Polytetrafluoroethylene	(CF ₂) _n	8,28	17,25	2,20
Polyvinylchloride	(C ₂ H ₃ Cl) _n	12,00	23,43	1,30
Polypropylene	(C ₃ H ₅) _n	5,39	10,66	0,90
Polycarbonate	(C ₁₆ H ₁₄ O ₃) _n	6,10	12,16	1,20

NOTES

1 Effective atomic number

2 Effective atomic weight

The quantities $\langle Z \rangle$ and $\langle A \rangle$ of a compound or a mixture are given by

$$\langle Z \rangle = \sum_j W_j Z_j \text{ and } \langle A \rangle = \langle Z \rangle (\sum_j W_j Z_j / A_j)^{-1}$$

where W_j , Z_j and A_j are the fraction by weight, the atomic number, and the atomic weight of the j^{th} atomic constituent, respectively.

Table 5 – Mass collision stopping power for electrons in some important insulators and other materials ($\text{MeV} \cdot \text{g}^{-1} \cdot \text{cm}^2$) [7]

Electron energy (MeV)	Carbon	Water (liq.)	Air (dry)	Poly-amide (Nylon -6)	Poly-ethylene	Poly-ethylene-terephthalate	Poly-methyl-methacrylate	Poly-styrene	Poly-tetra-fluoro-ethylene	Poly-vinyl-chloride	Poly-propylene	Poly-carbonate
0,1	3,671	4,115	3,633	4,152	4,384	3,832	4,006	4,034	3,421	3,604	4,287	3,920
0,15	2,883	3,238	2,861	3,263	3,443	3,015	3,152	3,172	2,697	2,843	3,367	3,084
0,2	2,482	2,793	2,470	2,813	2,967	2,603	2,719	2,735	2,330	2,457	2,902	2,660
0,3	2,083	2,355	2,084	2,369	2,497	2,195	2,292	2,305	1,968	2,077	2,443	2,242
0,5	1,782	2,034	1,802	2,032	2,142	1,889	1,957	1,984	1,699	1,793	2,098	1,930
0,7	1,673	1,917	1,706	1,906	2,008	1,776	1,856	1,864	1,600	1,690	1,969	1,813
1,0	1,609	1,849	1,661	1,832	1,930	1,710	1,788	1,794	1,534	1,633	1,893	1,748
1,5	1,584	1,822	1,661	1,801	1,895	1,684	1,760	1,766	1,522	1,615	1,860	1,719
2,0	1,587	1,824	1,684	1,802	1,895	1,686	1,762	1,768	1,525	1,623	1,861	1,721
3,0	1,611	1,846	1,740	1,823	1,917	1,709	1,784	1,791	1,546	1,653	1,883	1,744
5,0	1,658	1,892	1,833	1,870	1,965	1,756	1,832	1,839	1,589	1,708	1,931	1,791
10,0	1,730	1,968	1,979	1,946	2,042	1,831	1,908	1,916	1,657	1,791	2,008	1,867

Table 6 – Extrapolated range for electrons ¹⁾ in some important insulators and other materials ($\text{g} \cdot \text{cm}^{-2}$) [30]

<i>Electron energy (MeV)</i>	<i>Carbon</i>	<i>Aluminium</i>	<i>Water</i>	<i>Polyamide (Nylon-6)</i>	<i>Polyethylene</i>	<i>Polyethylene-terephthalate</i>	<i>Polymethylmethacrylate</i>
0,1	1,39 E-2	1,30 E-2	1,23 E-2	1,26 E-2	1,17 E-2	1,23 E-2	1,28 E-2
0,15	2,80 E-2	2,54 E-2	2,45 E-2	2,54 E-2	2,36 E-2	2,65 E-2	2,57 E-2
0,2	4,51 E-2	4,03 E-2	3,93 E-2	4,10 E-2	3,83 E-2	4,28 E-2	4,15 E-2
0,3	8,60 E-2	7,53 E-2	7,45 E-2	7,81 E-2	7,32 E-2	8,23 E-2	7,89 E-2
0,5	1,83 E-1	1,58 E-1	1,58 E-1	1,66 E-1	1,56 E-1	1,73 E-1	1,68 E-1
0,7	2,91 E-1	2,49 E-1	2,51 E-1	2,65 E-1	2,49 E-1	2,75 E-1	2,67 E-1
1,0	4,63 E-1	3,96 E-1	3,98 E-1	4,21 E-1	3,96 E-1	4,37 E-1	4,25 E-1
2,0	1,07 E+0	9,12 E-1	9,18 E-1	9,69 E-1	9,12 E-1	1,01 E+0	9,78 E-1
3,0	1,68 E+0	1,44 E+0	1,45 E+0	1,53 E-1	1,44 E+0	1,59 E+0	1,54 E+0
5,0	2,92 E+0	2,52 E+0	2,52 E+0	2,66 E+0	2,50 E+0	2,76 E+0	2,68 E+0
10,0	6,01 E+0	5,18 E+0	5,18 E+0	5,47 E+0	5,14 E+0	5,63 E+0	5,52 E+0
1) The penetration depth at the point where the tangent at the steepest point on the almost straight descending portion of the transmission curve for monoenergetic electrons normally incident on the slab-absorber meets the X-axis (transmission = 0).							

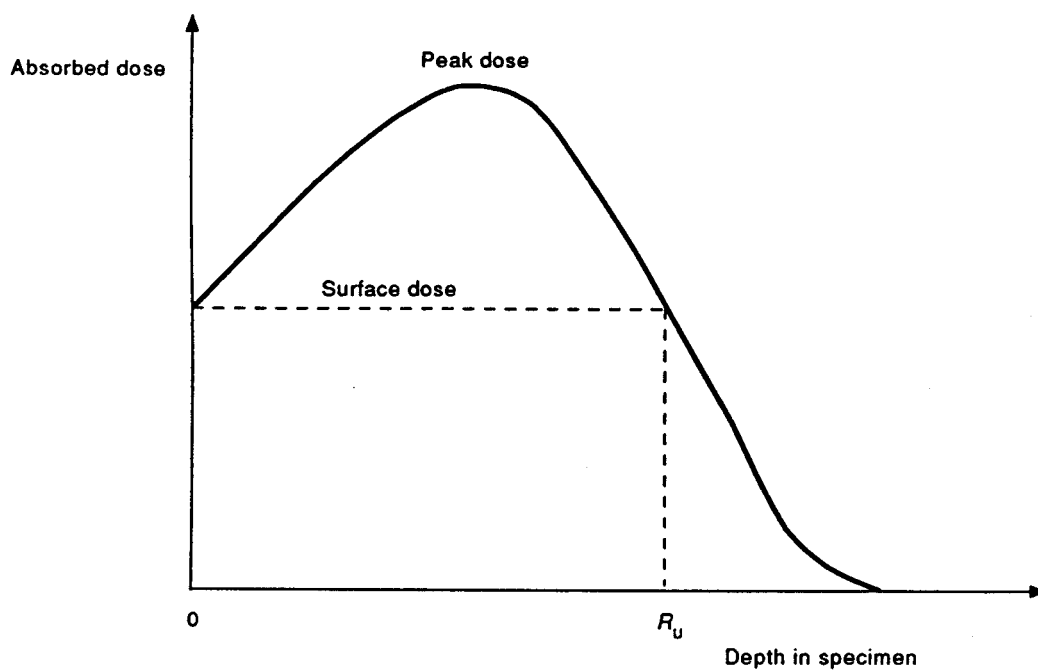


Figure 1 – A typical depth-dose distribution in a homogeneous material obtained with electron accelerators for radiation processing (acceleration voltage > 0,5 MV, R_u = useful range)

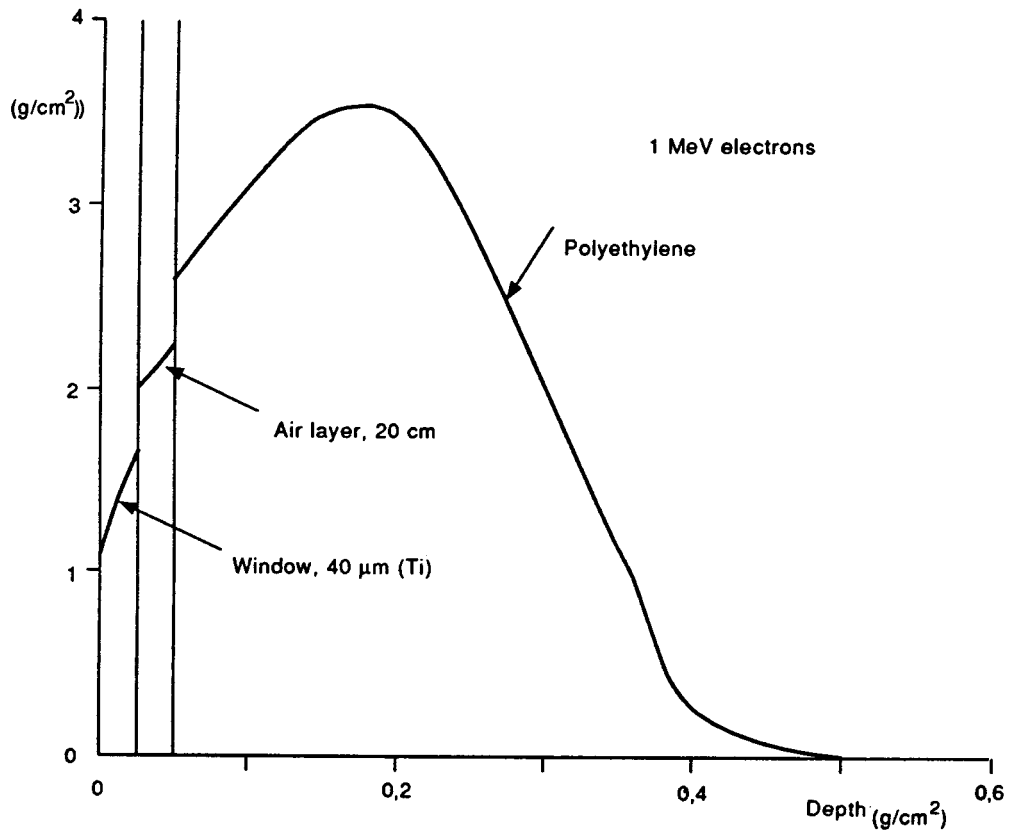


Figure 2 – An example of calculated results of energy deposition function, $I(z')$, for a slab layer of polyethylene exposed to 1 MeV electron (z' : total depth in three-layer absorber consisting of beam window, air gap, and polyethylene layer)

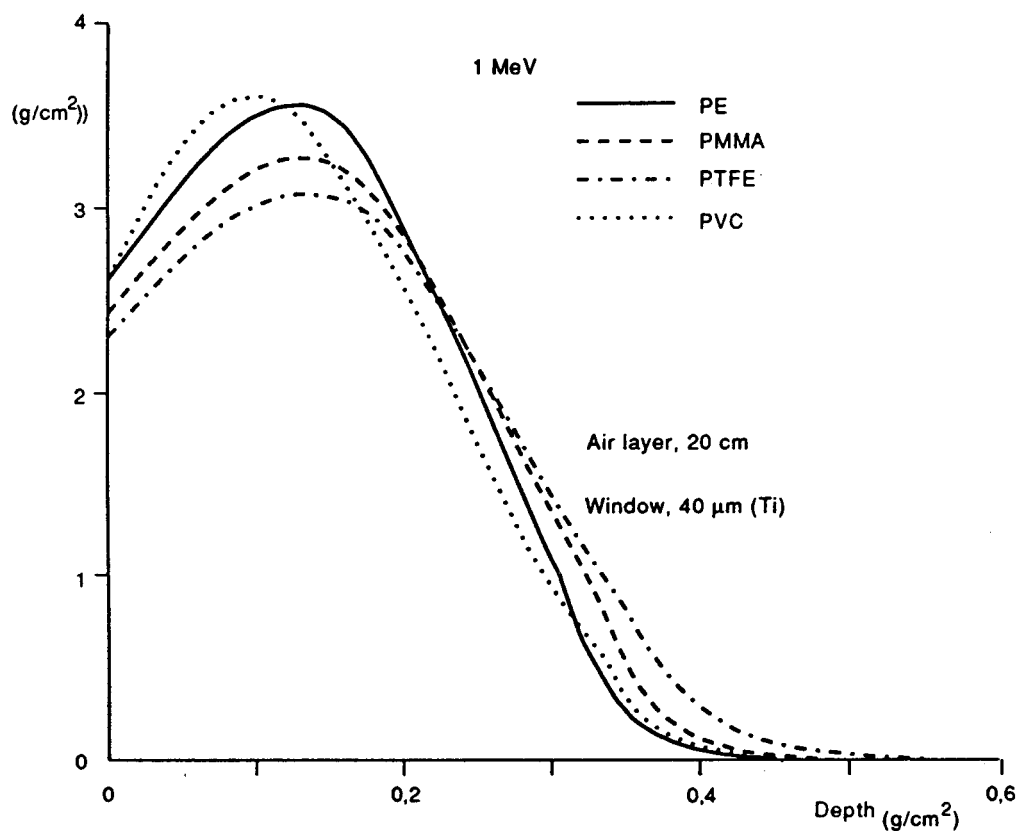
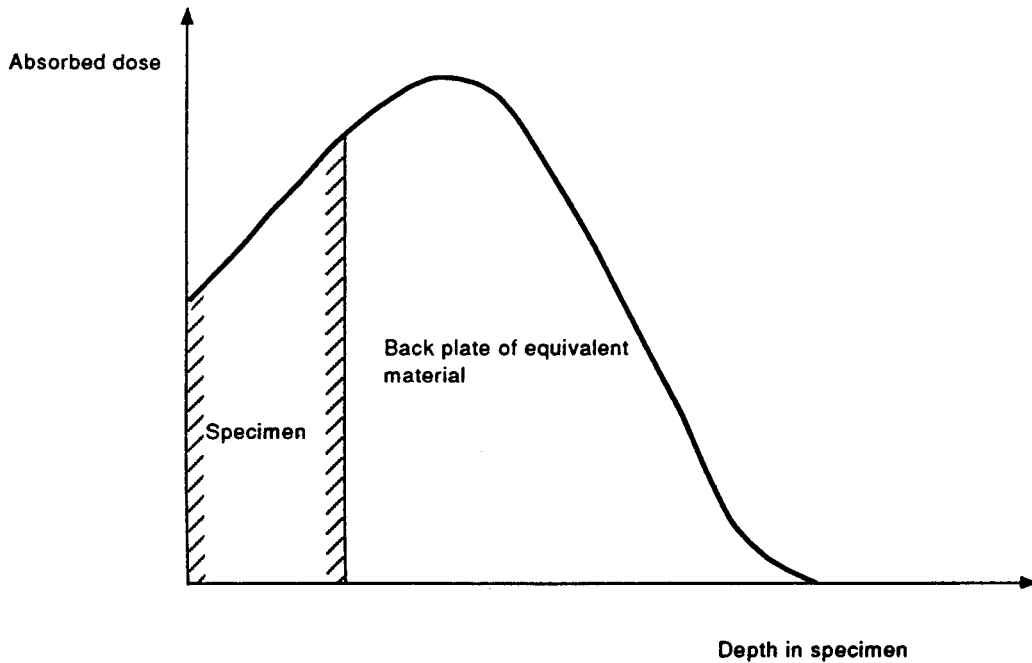
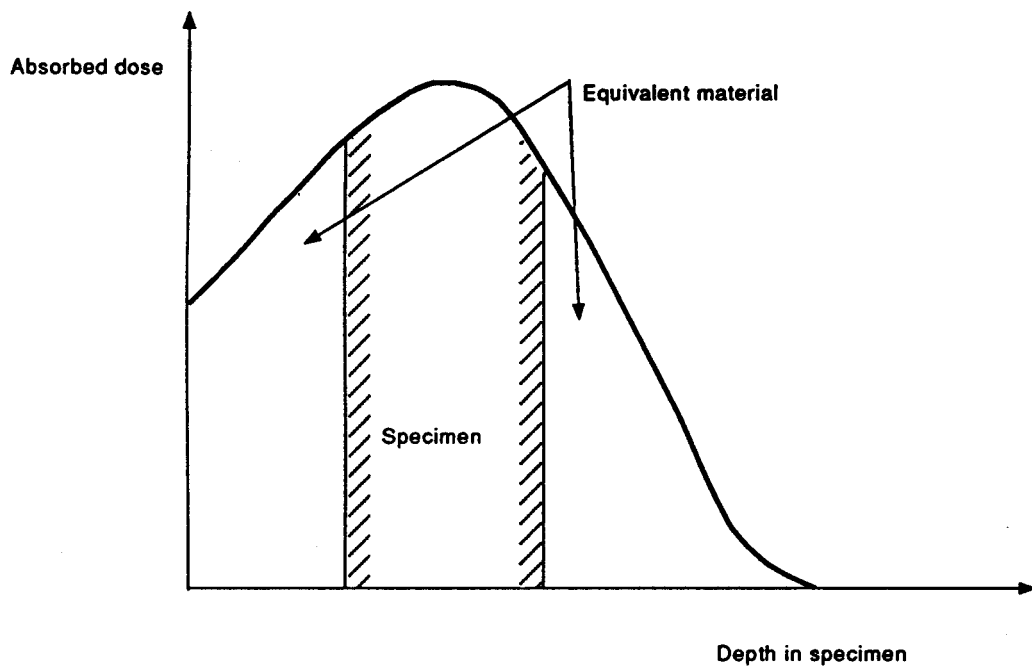


Figure 3 – An example of calculated results of energy deposition function, $I(z')$, for typical organic insulators exposed to 1 MeV electron (z' : total depth in three-layer absorber consisting of beam window, air gap, and insulating material layer)



a)



b)

Figure 4 – Two methods of arranging the irradiation samples in order to take into account the typical depth-dose distributions: a) specimen and a backplate of the equivalent material; b) specimen sandwiched between two plates of the equivalent material

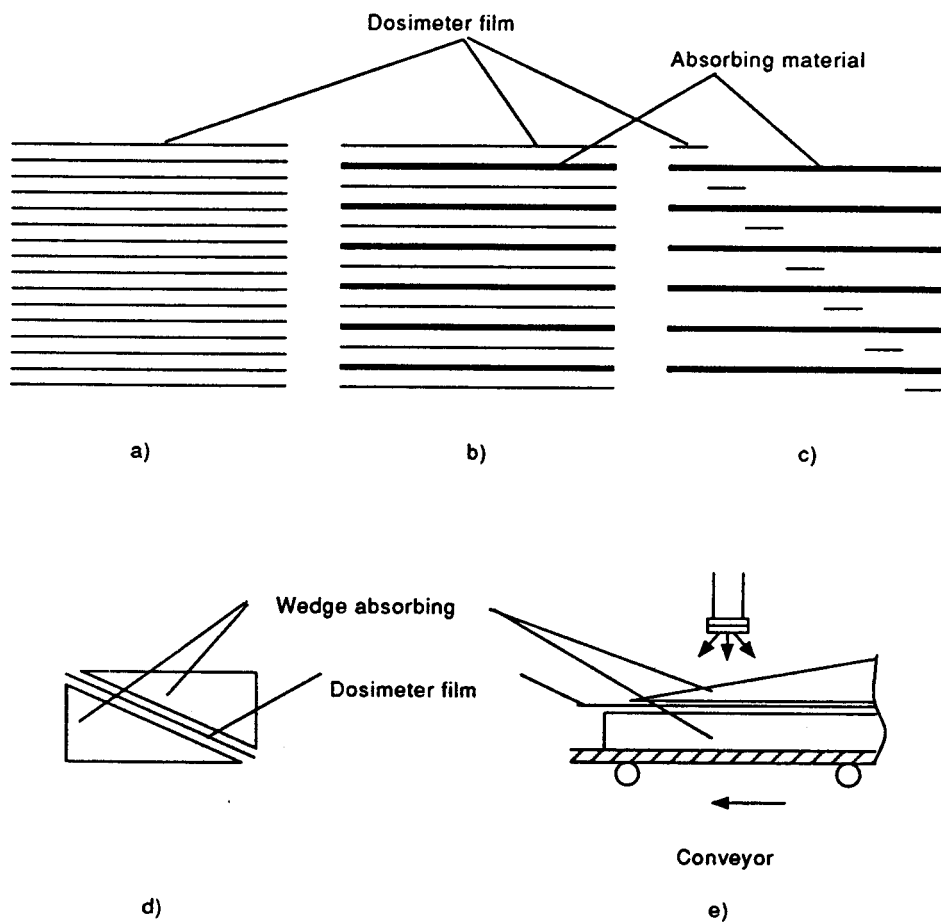


Figure 5 – Methods of arranging the irradiation samples for measuring electron depth-dose distributions with a stack of slab insulating materials and wedge-shape insulating materials: a) uniform stack method; b) alternate stack method; c) shift insertion method; d) linear wedge method, and e) stepped wedge method

Annex A (normative)

Charged-particle equilibrium thickness

Whenever a material is irradiated from one side only with X- or γ -rays uncontaminated with secondary electrons, there is initially (in the first absorber) a build-up of energy deposition (absorbed dose) as the radiation penetrates the material. After some finite thickness the radiation-energy deposition decreases. The thickness necessary to reach the maximum energy deposition is commonly called the charged-particle equilibrium thickness, and is a function of the radiation energy and the electron density of the material being irradiated. For larger thicknesses there is charged-particle equilibrium in the material.

Figure A.1 is a typical plot of energy deposition as a function of thickness. Whenever one is irradiating a specimen from all sides, it is necessary to surround the specimen with an absorber in order to ensure charged-particle equilibrium throughout the specimen. In practical cases with highly scattered radiation, build-up is not observed. It is recommended however to use built-up layers in order to provide well-defined irradiation conditions.

Figure A.2 is a plot of absorber thickness as a function of energy for material of electron density $3,3 \times 10^{23} \text{ cm}^{-3}$. Figure A.3 is a plot of thickness of water (or a material of the same electron density) as a function of energy for a given attenuation of unidirectional irradiation.

NOTE – The electron density n of any material can be evaluated from:

$$n = \rho \frac{N_A}{M} \sum_i Z_i [\text{cm}^{-3}] = \frac{N_A}{M} \sum_i Z_i [\text{g}^{-1}] \quad (\text{A.1})$$

where

ρ is the density of material (g/cm^3);

N_A is the $6,023 \times 10^{23} \text{ mol}^{-1}$, Avogadro's constant;

M is the molar mass (g/mol);

Z_i is the atomic number of element i ;

$\sum_i Z_i$ is the total number of electrons per molecule.

Since $1/M (\sum_i Z_i)$ is about $1/2$ for elements up to $Z = 17$ (excluding H), for organic materials this equation can be simplified to read:

$$n = \rho \frac{N_A}{2} 3 \times 10^{23} \text{ p}[\text{cm}^{-3}] = 3 \times 10^{23} [\text{g}^{-1}]$$

Figures A.1 to A.3 are calculated with this approximation.

The curve in figure A.2 will shift to the left as the electron density of the absorber increases above this calculated value and to the right for materials of lesser electron density. Therefore, an equivalent thickness to use is that obtained from figure A.2 divided by the ratio of the electron density of the absorber to $3,3 \times 10^{23} \text{ cm}^{-3}$ (electron density of

water).

For example, it is required to irradiate polytetrafluoroethylene (PTFE) film with 1,1 MeV photons. Referring to figure A.2, it is noted that 0,5 cm of material of electron density of $3,3 \times 10^{23} \text{ cm}^{-3}$ is needed to ensure charged-particle equilibrium. Therefore, this thickness of water shall surround the film.

For PTFE with a density of $\rho = 2,2 \text{ g/cm}^3$ one calculates:

$$\frac{n_{\text{PTFE}}}{n_{\text{H}_2\text{O}}} = \frac{3 \times 10^{23} \times 2,2}{3,3 \times 10^{23}} = 2$$

and

$$d_{\text{PTFE}} = \frac{d_{\text{H}_2\text{O}}}{n_{\text{PTFE}} / n_{\text{H}_2\text{O}}} = 0,25 \text{ cm}$$

This means that 0,25 cm of PTFE must surround the film.

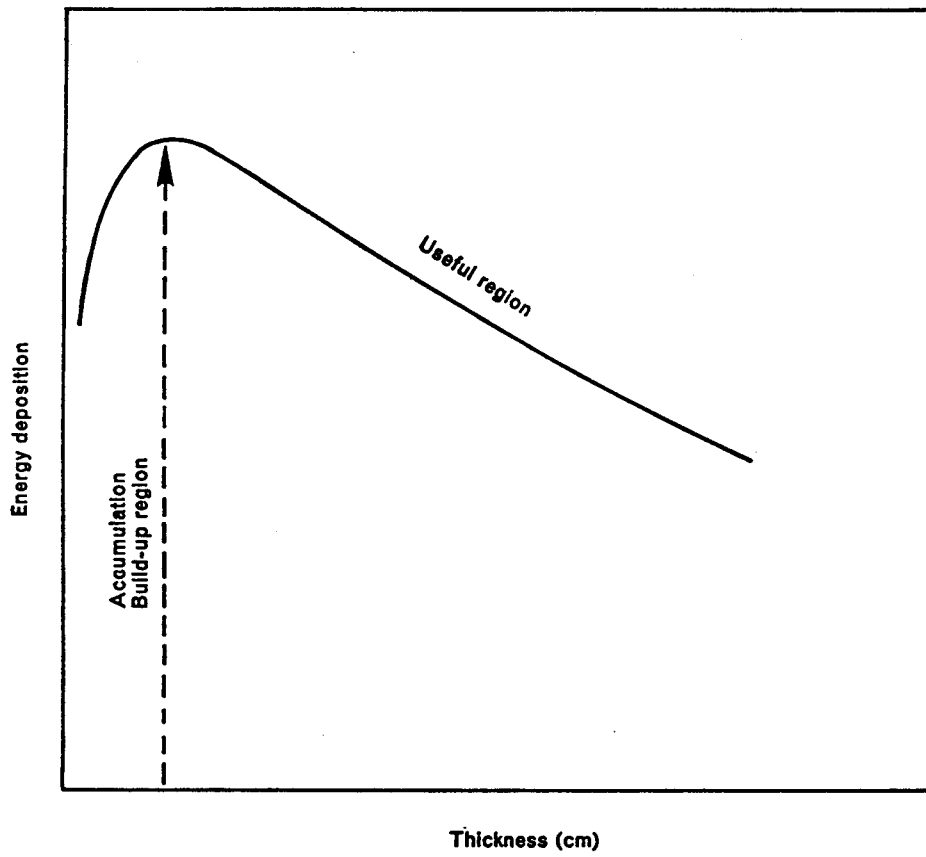


Figure A.1 – Absorbed dose as a function of thickness. The part of the curve to the left of the maximum is not well known; therefore, it is necessary to have a sample of sufficient thickness to fall either at or to the right of the maximum

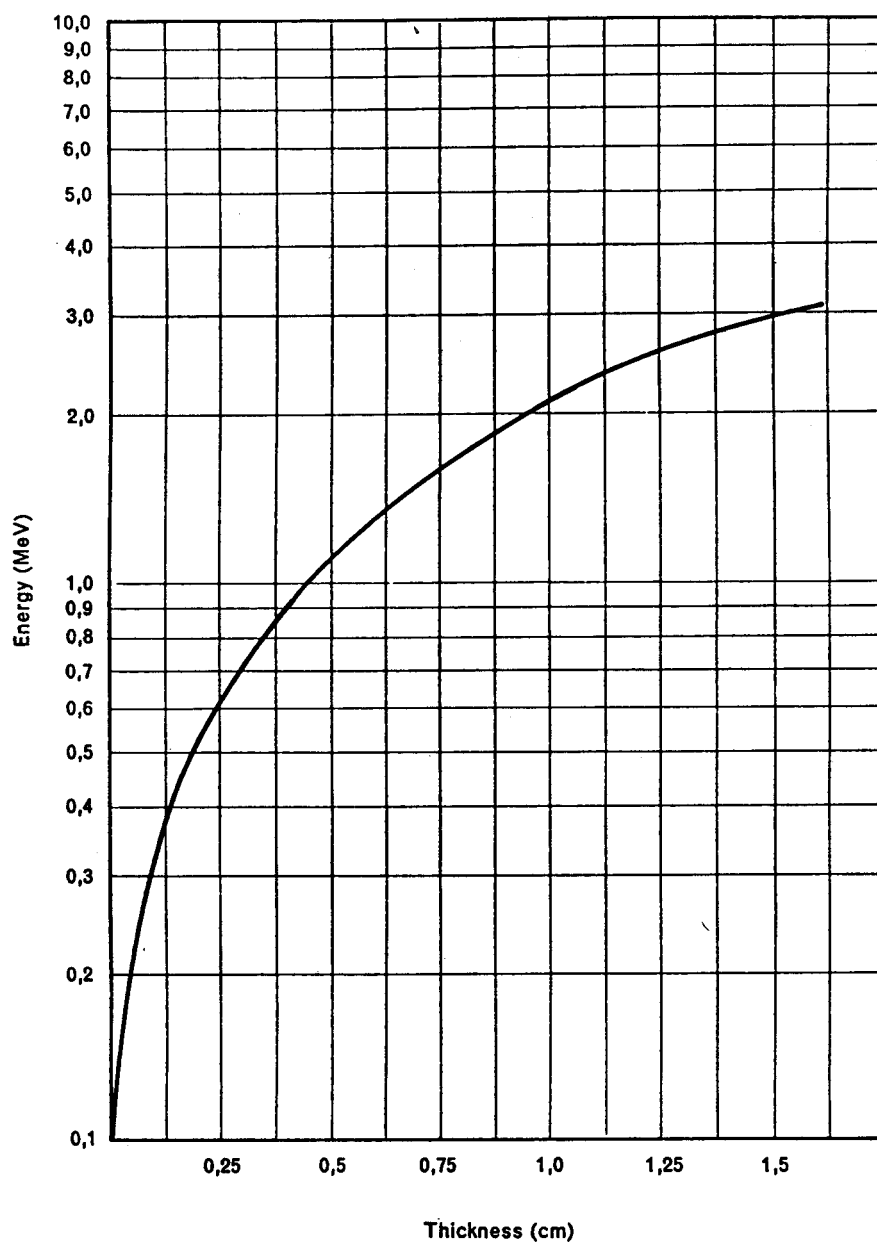


Figure A.2 – Absorber thickness for charged-particle equilibrium as a function of energy for a material with an electron density of $3,3 \times 10^{23} \text{ cm}^{-3}$ (water)

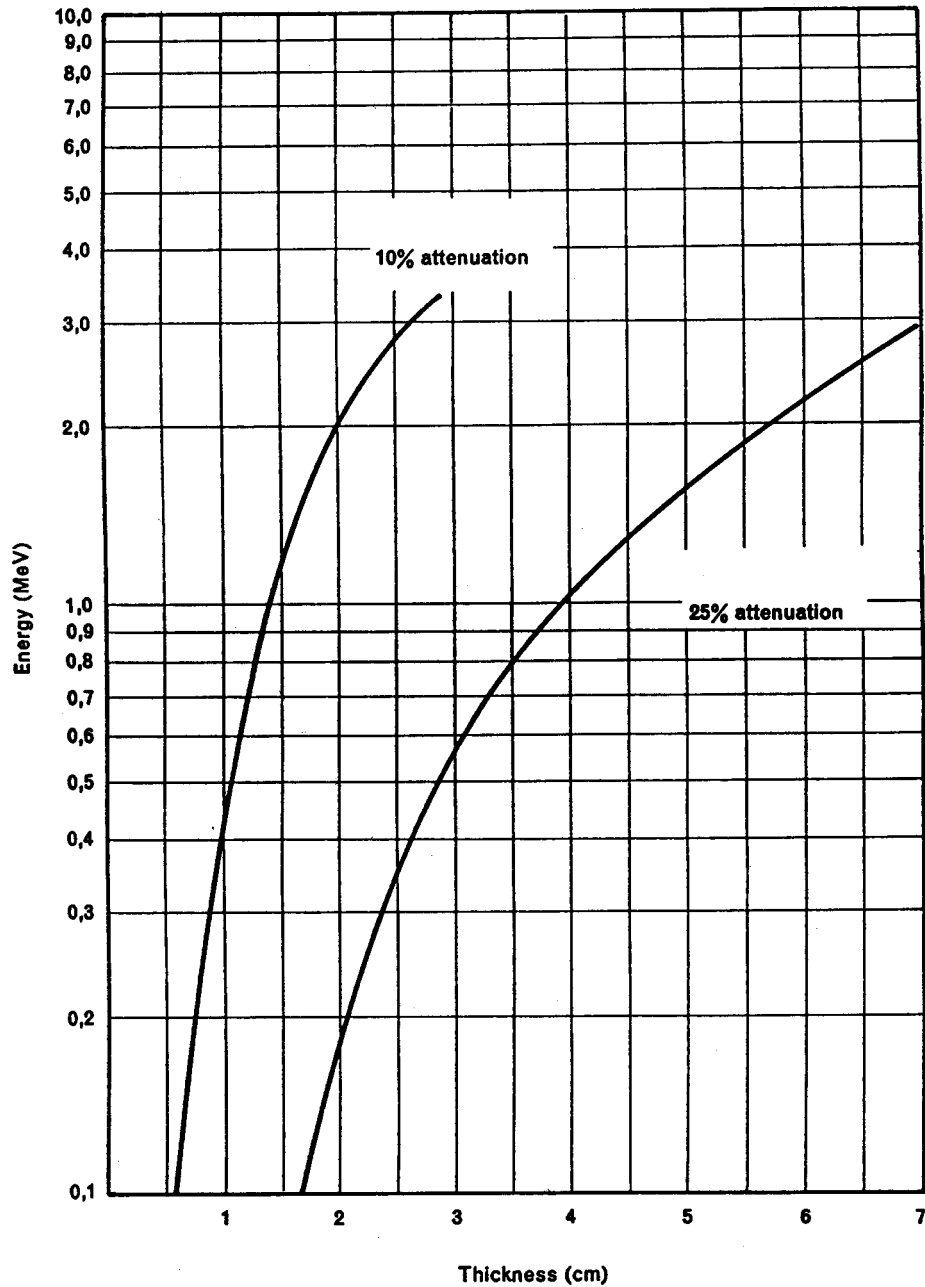


Figure A.3 – Thickness of water (1 g/cm^3) as a function of photon energy for a given attenuation of unidirectional X-ray or γ -ray radiation

Annex B (normative)

Derivation of numerical factors f_i

The efficiency of energy absorption by a material exposed to X- or γ -radiation is determined by its mass energy-absorption coefficient $(\mu_{en}/\rho)_m$.

This may be determined from the mass absorption coefficient by including only the fraction of the photon energy actually absorbed by the material; corrections are therefore required for fluorescence, scattering, annihilation, radiation, and bremsstrahlung losses.

The value for the material being irradiated, whether a compound or a mixture, may be closely approximated by the relation:

$$(\mu_{en}/\rho)_m = \sum_i W_i (\mu_{en}/\rho)_i \quad (B.1)$$

where W_i and $(\mu_{en}/\rho)_i$ are, respectively, the mass fraction and the mass energy-absorption coefficient of constituent i .

An exposure in air of 1 C/kg results in an absorption of 33,68 J/kg (based on 33,7 + 0,2 eV for production of one ion pair in air) whenever charged-particle equilibrium exists at the point of interest. For the same exposure, the absorbed dose received by the material being irradiated is given by the equation:

$$D_m = D_{air} \frac{(\mu_{en}/\rho)_m}{(\mu_{en}/\rho)_{air}} = 33,68 \frac{(\mu_{en}/\rho)_m}{(\mu_{en}/\rho)_{air}} X \quad (B.2)$$

where

- D_m is the absorbed dose in the material m in Gy;
- D_{air} is the absorbed dose in air in Gy;
- $(\mu_{en}/\rho)_m$ is the mass energy-absorption coefficient for the material m ;
- $(\mu_{en}/\rho)_{air}$ is the mass energy-absorption coefficient for air;
- X is the exposure in C/kg.

Substitution of equation (B.1) into equation (B.2) gives:

$$D_m = X \sum_i W_i f_i \quad (B.3)$$

where

$$f_i = 33,68 \frac{(\mu_{en}/\rho)_i}{(\mu_{en}/\rho)_{air}} \quad (J/C) \quad (B.4)$$

NOTE – The numerical factor f_i can also be given in the old c.g.s. unit rad/R (1 rad/R = 38,76 J/C):

$$f_i = 0,870 \frac{(\mu_{en}/\rho)_i}{(\mu_{en}/\rho)_{air}} \quad (rad/R)$$

Annex C

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